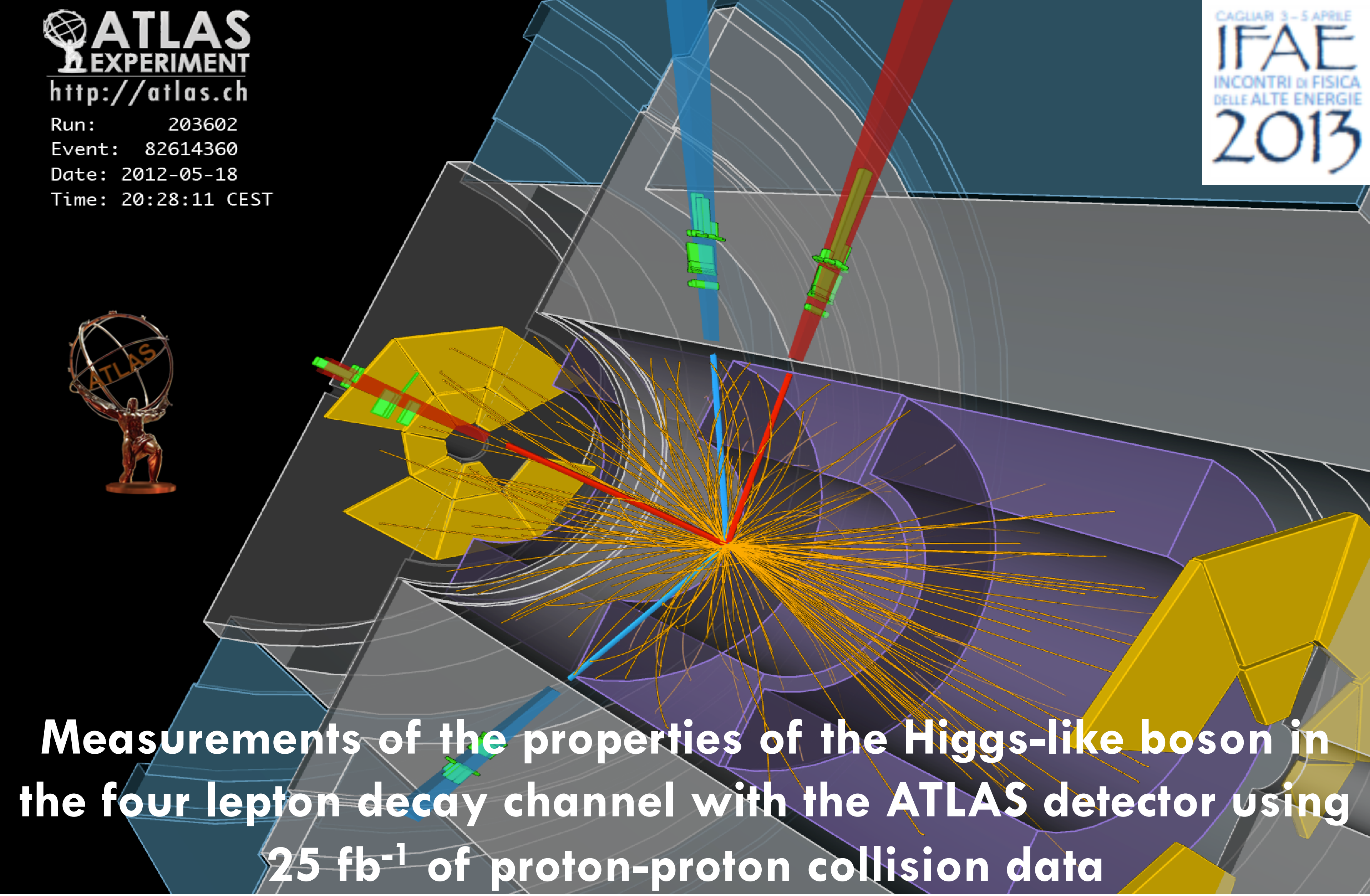

IFAE INCONTRI DI FISICA DELLE ALTE ENERGIE 2013
CAGLIARI 3-5 APRILE

Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data

IFAE 2013
Cagliari 3-5 Aprile

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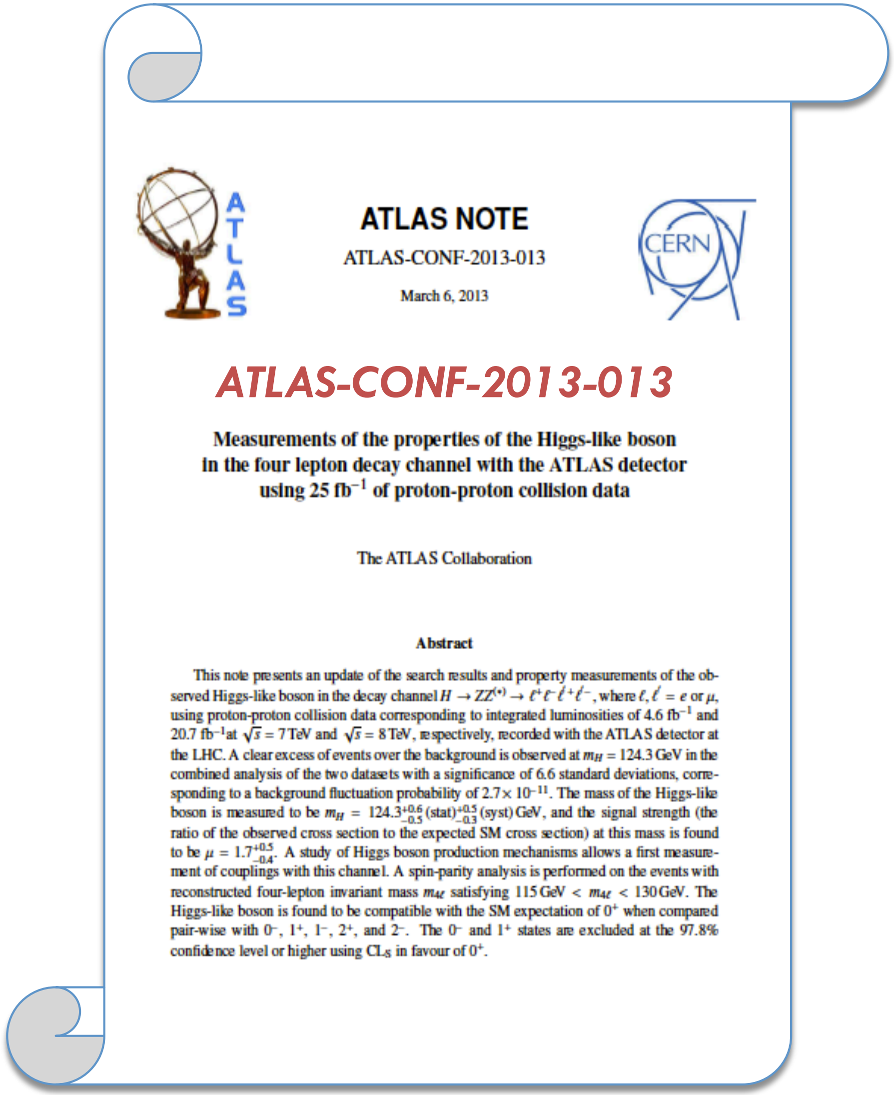
Introduction

After the July 2012 discovery and the December 2012 update:

- Full 2011-2012 ATLAS dataset: 4.6 fb^{-1} @ 7 TeV, 20.7 fb^{-1} @ 8 TeV
- Updated and new studies of the Higgs-like resonance:
  - mass
  - signal strength
  - couplings
  - spin-parity
- Improved analysis, different production signatures (ggF/VBF/VH) categorized



ATLAS NOTE

ATLAS-CONF-2013-013

March 6, 2013

ATLAS-CONF-2013-013

Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data

The ATLAS Collaboration

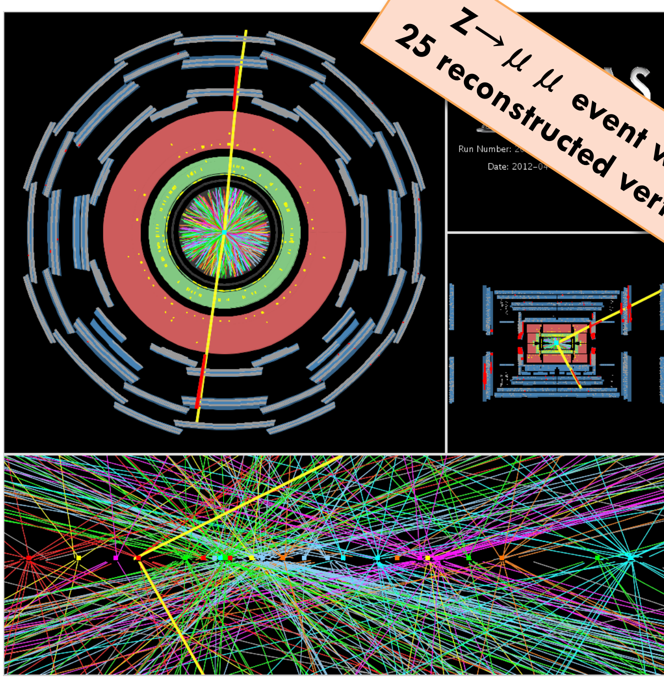
Abstract

This note presents an update of the search results and property measurements of the observed Higgs-like boson in the decay channel $H \to ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e$ or μ, using proton-proton collision data corresponding to integrated luminosities of 4.6 fb^{-1} and 20.7 fb^{-1}at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively, recorded with the ATLAS detector at the LHC. A clear excess of events over the background is observed at $m_H = 124.3$ GeV in the combined analysis of the two datasets with a significance of 6.6 standard deviations, corresponding to a background fluctuation probability of 2.7×10^{-11}. The mass of the Higgs-like boson is measured to be $m_H = 124.3^{+0.6}_{-0.5}$ (stat)$^{+0.5}_{-0.3}$ (syst) GeV, and the signal strength (the ratio of the observed cross section to the expected SM cross section) at this mass is found to be $\mu = 1.7^{+0.5}_{-0.4}$. A study of Higgs boson production mechanisms allows a first measurement of couplings with this channel. A spin-parity analysis is performed on the events with reconstructed four-lepton invariant mass $m_{4\ell}$ satisfying 115 GeV $< m_{4\ell} <$ 130 GeV. The Higgs-like boson is found to be compatible with the SM expectation of 0^+ when compared pair-wise with 0^-, 1^+, 1^-, 2^+, and 2^-. The 0^- and 1^+ states are excluded at the 97.8% confidence level or higher using CL_S in favour of 0^+.

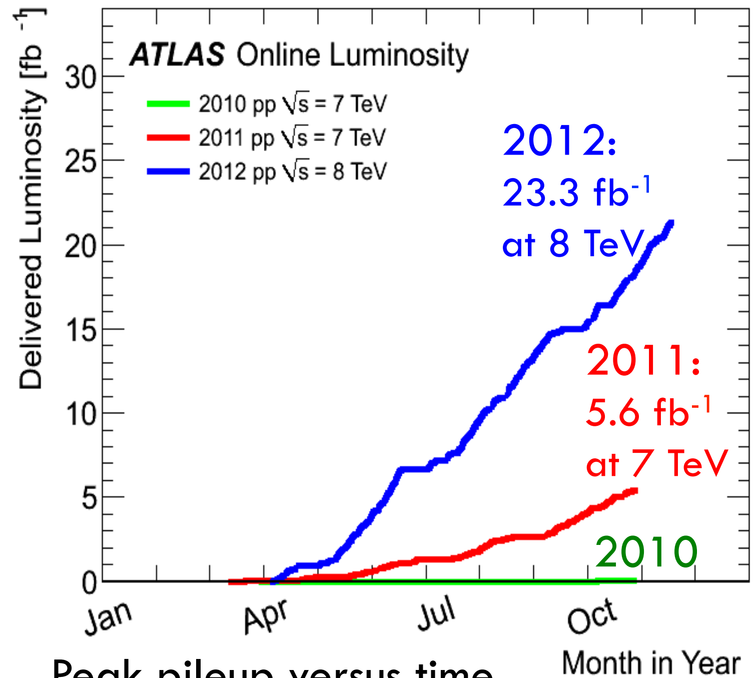
https://cds.cern.ch/record/1523699/files/ATLAS-CONF-2013-013.pdf

LHC and ATLAS preformances

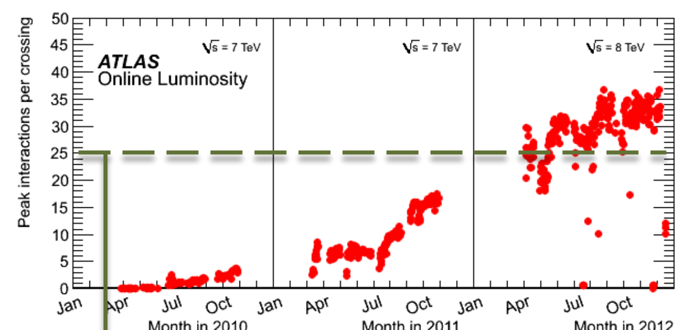
Excellent ATLAS performance
Data-taking efficiency: 93%
Good quality data fraction used for analysis: 95.8%
Challenge: harsh pile-up conditions [trigger, computing, reconstruction of physics objects]



$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

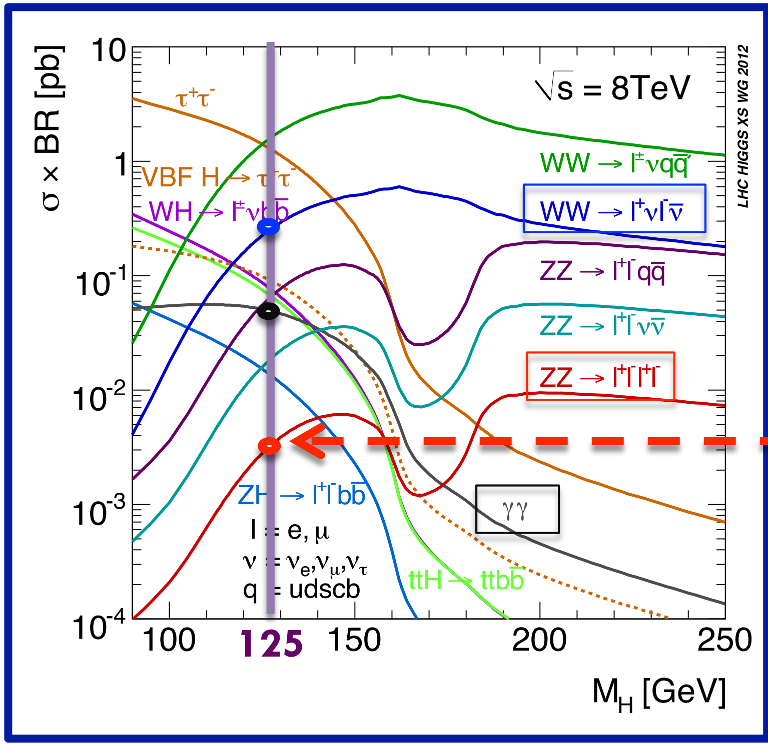


Peak pileup versus time



Design value (expected to be reached at $L=10^{34}$!)

The golden channel

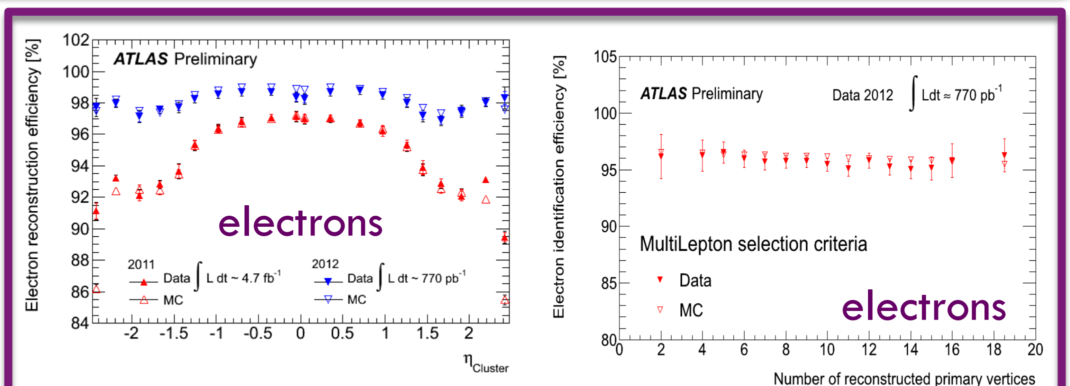


- ✧ **Fully reconstructible**
- ✧ **High S/B ratio**
- ✧ **Very low σ·Br**

$\sigma_H(m_H=125\ \text{GeV}) \approx 22\ (17)$ pb @ $\sqrt{s}= 8\ (7)$TeV

$BR(H\rightarrow 4l) = 2.7 \times 10^{-4}$

- ✧ **Requires excellent performance for electrons and muons**



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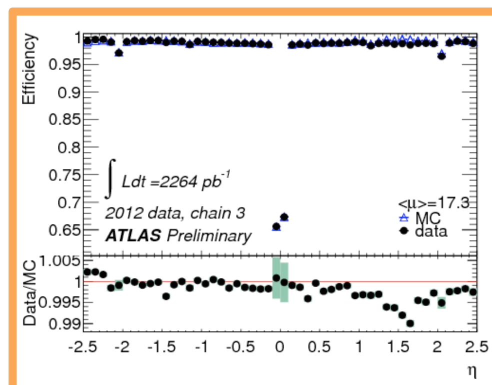

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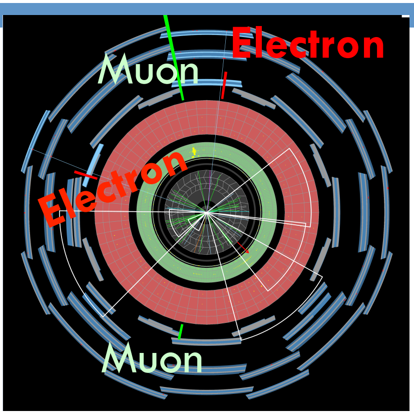
Event Selection

Preselection: Trigger & Lepton ID

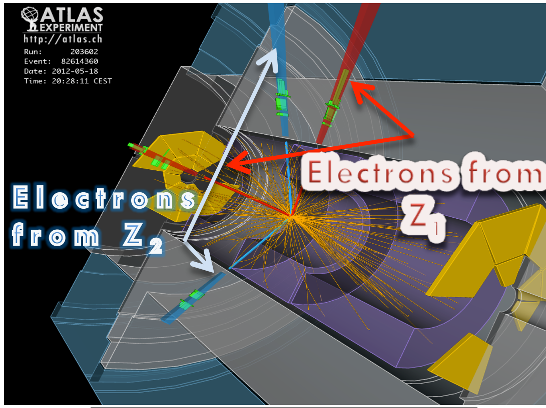
- **Electrons (GSF brem fit):** *E_T > 7 GeV and $|\eta|$ < 2.47 Tightened cut-based ID*
- **Muons:**
  - combined or segment-tagged muons: *p_T> 6 GeV $|\eta|$ < 2.7*
  - calo-tagged muons *p_T > 15 GeV $|\eta|$ < 0.1*
  - standalone muons *p_T > 6 GeV $|\eta|$ < 2.7*
  - FSR recovery



Kinematic Selection: 1 leptonic quadruplet

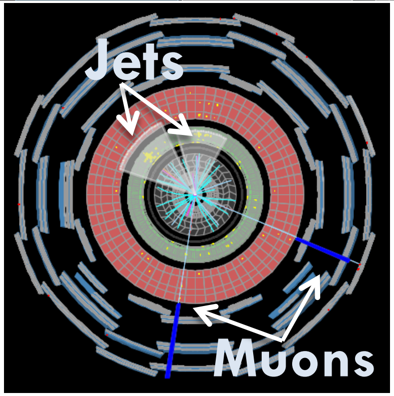
(2 SFOS lepton pairs)

- p_{T1}>20GeV, p_{T2}>15 GeV, p_{T3}>10 GeV
- **Z_1** Leading pair: 50 GeV < *m_{12} < 106 GeV*
- **Z_2** *Subleading pair: $M_{threshold}$ < m_{34}< 115 GeV*
  $M_{threshold}$ =12 (50) for m_{4l}≤140 (≥190)GeV
- *Lepton Overlap removing: ΔR>0.1 (0.2) between same (opposite) flavour leptons*
- *J/Ψ veto for the 4e,4μ subchannel*



Isolation and Impact parameter significance

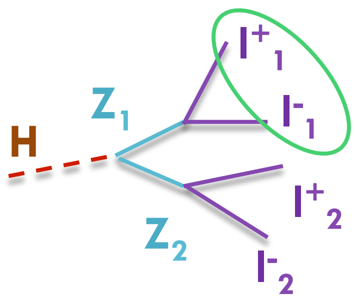
- Lepton track isolation (Δ*R = 0.20): Σ p/ p< 0.15*
- Leptonn calorimeter isolation (Δ*R = 0.20) : ΣE_T /E_T < 0.20 for electrons and ΣE_T /E_T < 0.30 for muons*
- $|d_0/\sigma(d_0)|$<3.5 (6.5) for muons (electrons)



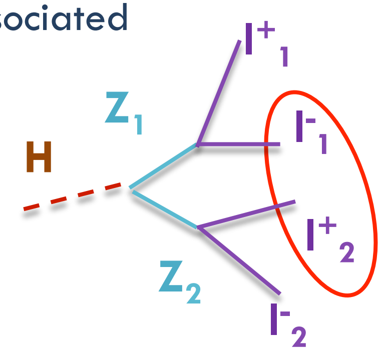
Overall acceptance for m_H=125 GeV @ 8TeV:
39% 4μ, 26% 2e2μ, 19% 4e (from 37% 4μ, 23% 2e2μ, 20% 4e)

Improvements in the analysis

Good-paired candidates: the two lepton pairs are correctly associated



Wrong-paired candidates: the two lepton pairs (4μ, 4e) are wrongly associated



Only for 4e and 4mu channel

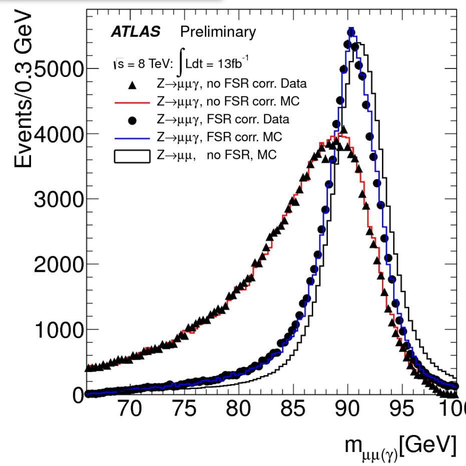
- **Reduction of the mispairing effect:** with the new selection the mispair effect is <10%

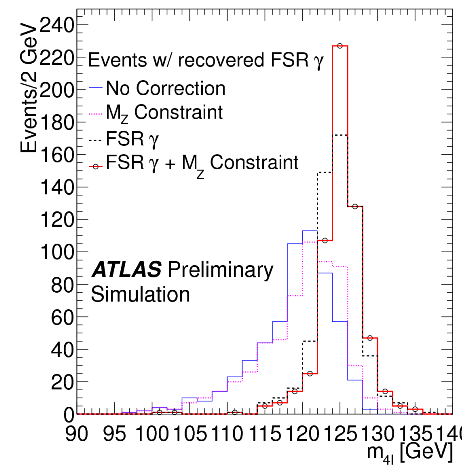
  (~20% December 2012)

- **Improved Mass Reconstruction:**
  - Muon p FSR-corrected if γ found with:

    E_T>1 (3.5) GeV and ΔR<0.08 (0.15)
  - Only applied on leading muons with:

    66 GeV<$m_{\mu\mu}$<89 GeV and $m_{\mu\mu\gamma}$ <100.0 GeV
  - ε=70% for FSR photons within acceptance and Purity=85%
  - 4% of H→ZZ(*)→μμℓℓ events corrected in MC for m_H=125 GeV





- **Z-mass constraint:**
  - on leading lepton pair;
  - for m_{4l}>190 GeV also on subleading pair

m_H=125 GeV	4μ	2μ2e / 2e2μ	4e
Gaussian mean	124.88±0.02 GeV	124.39±0.02 GeV	123.71±0.05 GeV
Gaussian width	1.62±0.02 GeV	1.90±0.02 GeV	2.40±0.05 GeV
Tails (outside 2σ)	16%	22%	21%
Improvement on σ	19%	16%	12%

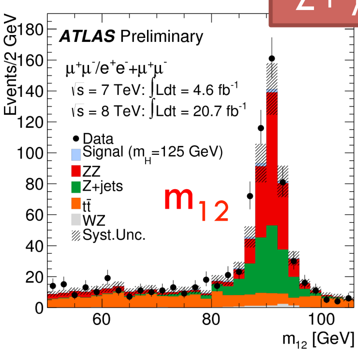
Background Estimate

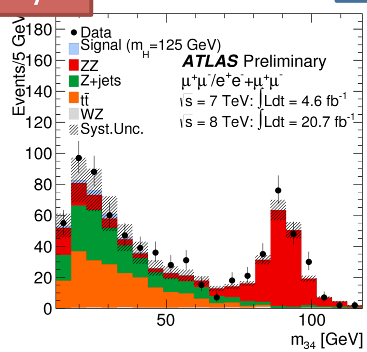
- ZZ: main, irreducible background
  - estimated from MC (POWHEG+gg2ZZ+SHERPA)
  - normalized to MCFM cross-section
- Reducible background: Z+jets (including Zbb), tt:
  - data-driven using control regions with relaxed / inverted selection
  - transfer factors from data or MC (cross-checked with data)
  - Several methods to cross-check estimates

Z+μ μ

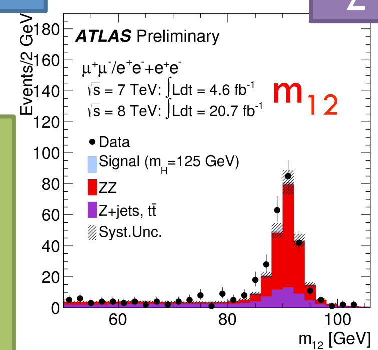
Reducible Background

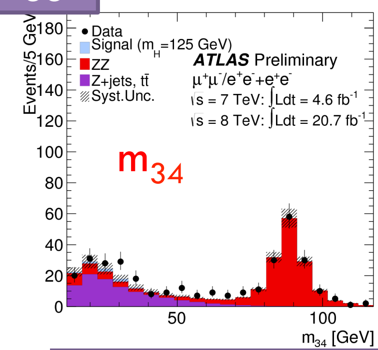
Z+ee



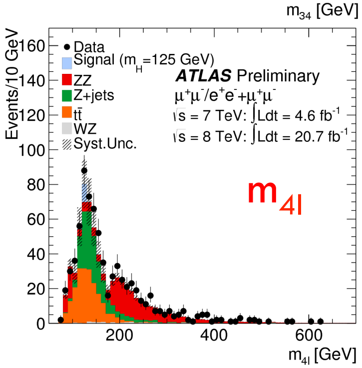


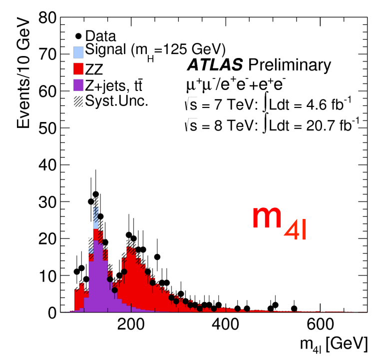
Control Region definition:
- ✧Opposite sign sub-leading pair
- ✧No isolation or IP signicance cuts





Background sources: tt, Zbb, Z+light jets





Background sources: conversion, light jets, heavy flavor fake electrons

Details in G. Mancini's poster

Systematics for the inclusive analysis

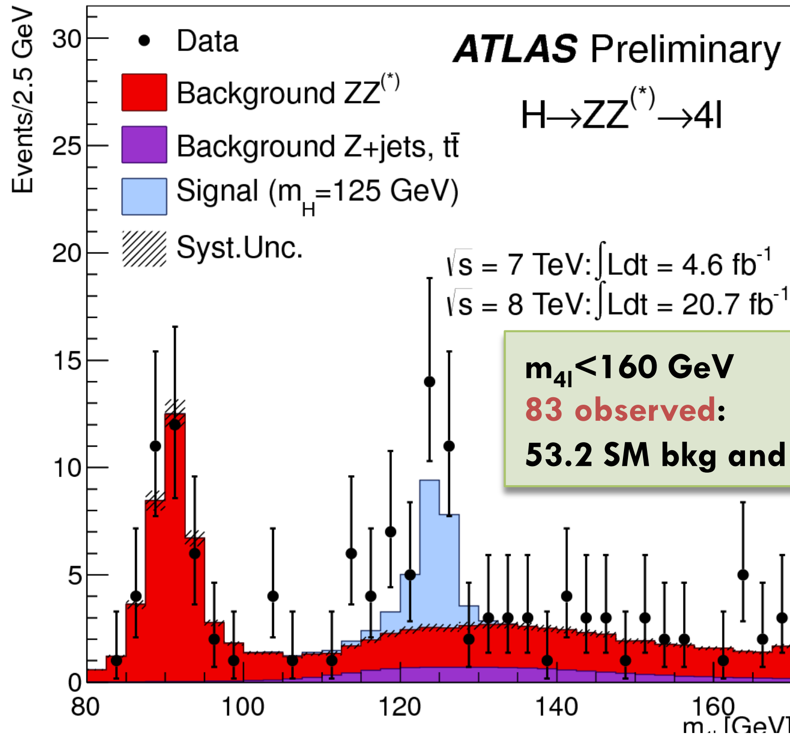
Signal rate	
Luminosity	1.8% (2011), 3.6% (2012)
Signal cross-section – scale	+7/-8% (ggF), 1% (VBF, VH)
– PDF	8% (gg), 4% (qq)
ggF p_T-reweighting	1%
$ZZ^{(*)}$ cross-section & shape – scale	5%
– PDF, α_s	8% (gg), 4% (qq)
Reducible background rate & shape	~30% (Z+μμ), ~20% (Z+ee)
Electron identification – signal @ m_H=125 GeV)	9.4% (4e), 8.7% (2μ2e), 2.4% (2e2μ)
– signal @ m_H=1 TeV)	2.4% (4e), 1.8% (2μ2e), 1.6% (2e2μ)
Muon identification	0.8% (4μ), 0.4% (2μ2e), 0.4% (2e2μ)
Mass measurement	
Electron energy scale and resolution	0.4% (4e), 0.2% (2e2μ)
Low-E_T electrons, QED FSR, background	<0.1%
Muon momentum scale and resolution	0.2% (4μ), 0.1% (2μ2e)

Electron and photon energy scale systematics fully correlated (from Z→ee based calibration)
Additional theoretical and experimental uncertainties for VBF-like and VH-like categories!

H→ZZ(*)→4l Inclusive Analysis: last updated results

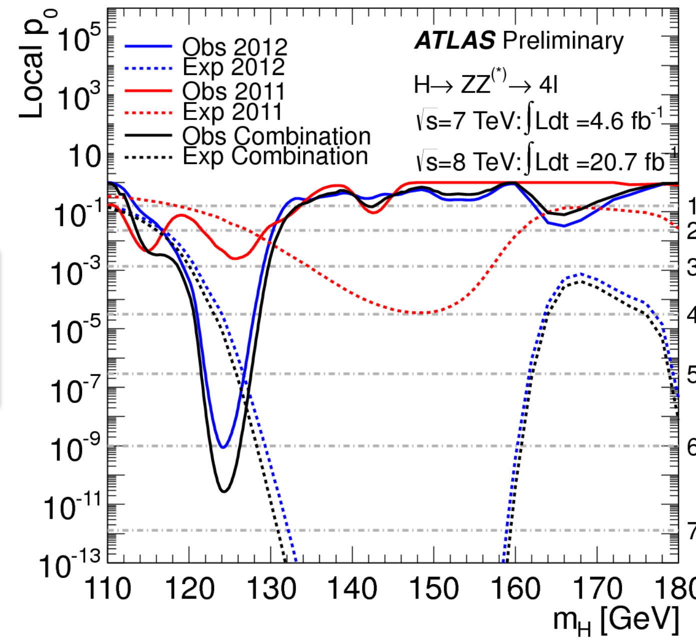
32 events observed with ≈11 (bkg) and ≈16 (signal) expected

(120 < m_H < 130 GeV)



m_{4l}<160 GeV
83 observed:
53.2 SM bkg and 18.2 SM signal

Observed significance is 6.6 σ

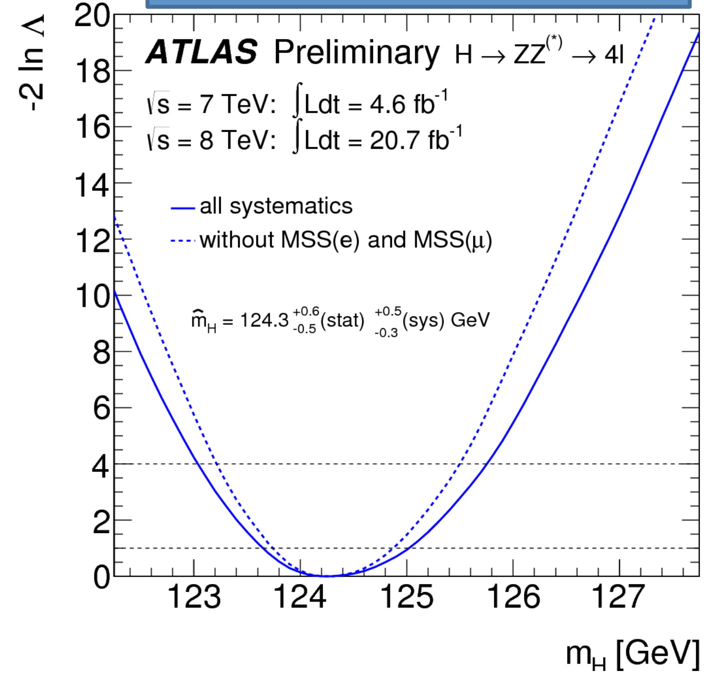


	total signal full mass range	signal 120-130 GeV	$ZZ^{(*)}$	$Z+$jets, $t\bar{t}$	S/B	expected	observed
4μ	6.8 ± 0.8	6.3 ± 0.8	2.8 ± 0.1	0.55 ± 0.15	1.9	9.6 ± 1.0	13
$2\mu 2e$	3.4 ± 0.5	3.0 ± 0.4	1.4 ± 0.1	1.56 ± 0.33	1.0	6.0 ± 0.8	5
$2e2\mu$	4.7 ± 0.6	4.0 ± 0.5	2.1 ± 0.1	0.55 ± 0.17	1.5	6.6 ± 0.8	8
$4e$	3.3 ± 0.5	2.6 ± 0.4	1.2 ± 0.1	1.11 ± 0.28	1.1	4.9 ± 0.8	6
total	18.2 ± 2.4	15.9 ± 2.1	7.4 ± 0.4	3.74 ± 0.93	1.4	27.1 ± 3.4	32

Mass Measurement

Inclusive analysis (no ggF/VBF/V-like categories)

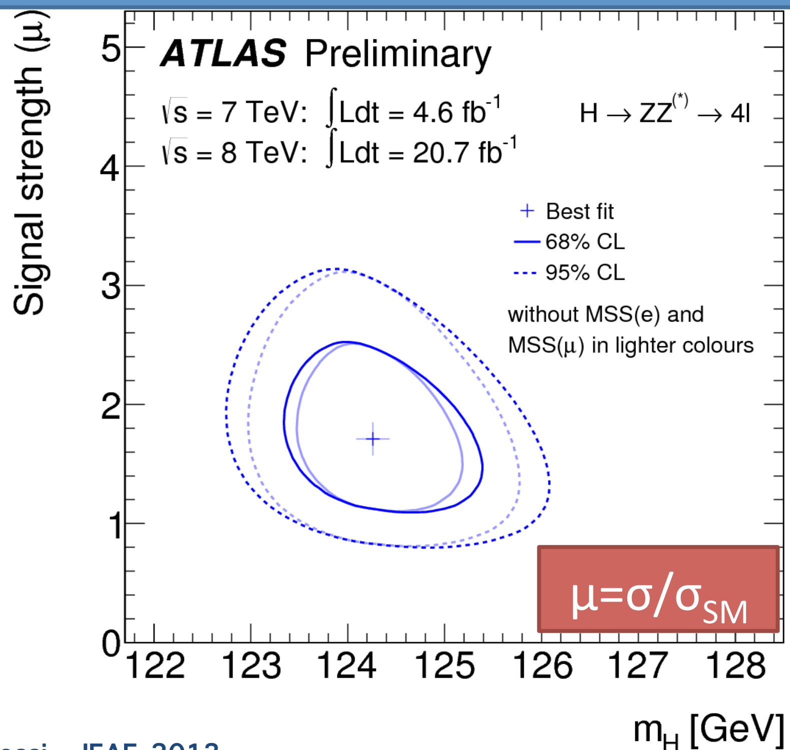
profile Likelihood vs. m_H



Fitted mass is:

$124.3\ ^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst)

profile Likelihood ratio contours on (m_H, μ) plane



$\mu = \sigma/\sigma_{SM}$

Fitted signal strenght at the best fit mass is:

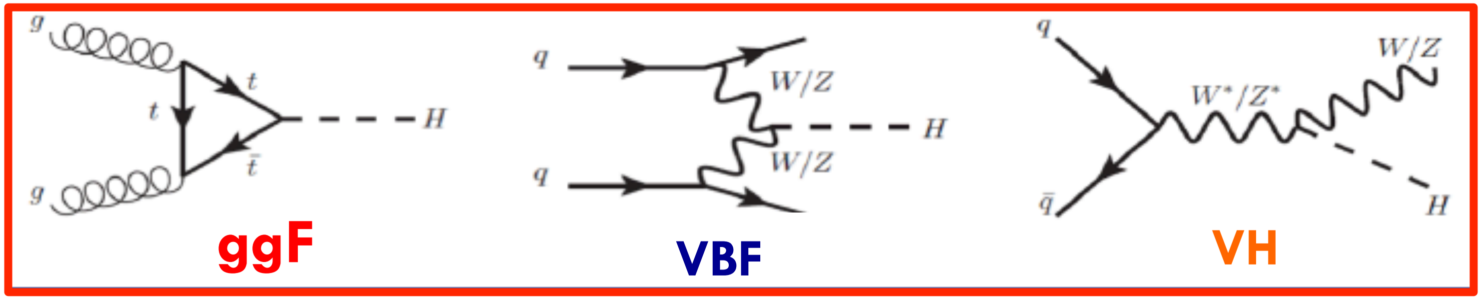
$\mu = 1.7^{+0.5}_{-0.4}$ @ m_H=124.3 GeV

Combined fit with $\gamma\gamma$ (*see M. Fanti's talk*):

$\mu = 1.5 \pm 0.4$ @ m_H=125.5 GeV

Details in N. Bruscino's poster

Event categorization

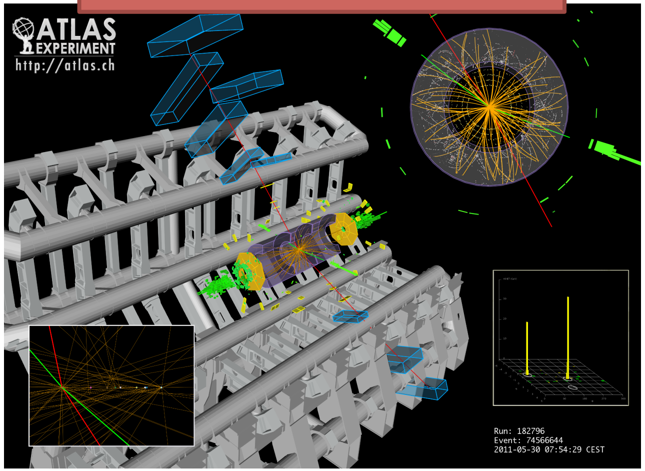


H→4l selection —YES→ **VBF selection** (N_{jets}>2 | $\eta_{J1} - \eta_{J2}$|>3 $m_{J1,J2}$ > 350 GeV) —YES→ **VBF-like**

VBF selection —NO→ **VH selection** (Additional lepton with p_T > 8 GeV) —YES→ **VH-like**

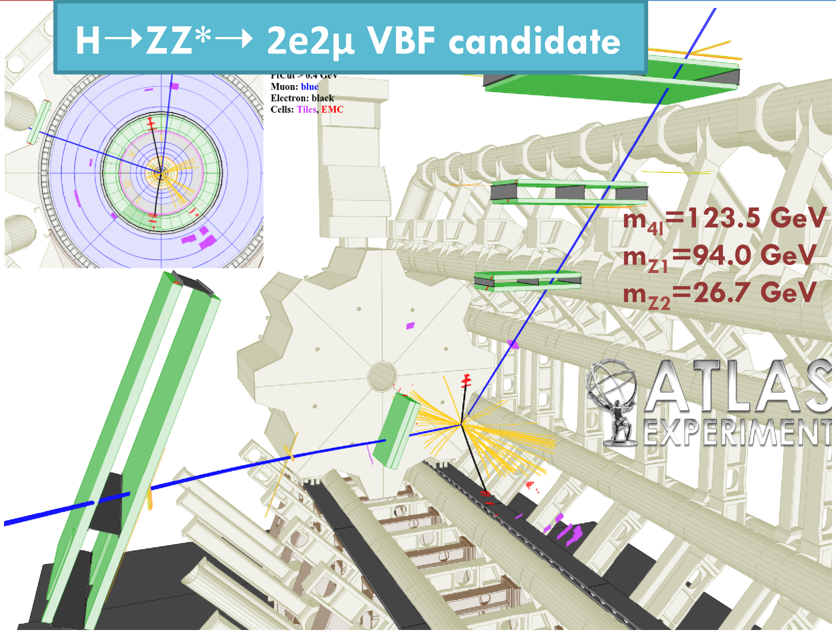
VH selection —NO→ **ggF-like**

VBF candidate event



Vector-boson candidates

H→ZZ*→ 2e2μ VBF candidate



Expected signal (m_{4l}>100 GeV)

category	ggF (+ttH)	VBF	VH	ZZ*
Data 8 TeV				
ggF	13.5	0.79	0.65	320.4
VBF	0.28	0.43	0.01	3.58
VH	0.06	-	0.14	0.69
Data 7 TeV				
ggF	2.2	0.14	0.11	57.5
VBF	0.03	0.06	0.01	0.44
VH	0.01	-	0.03	0.25

One VBF candidate in (m_{4l}=120-130 GeV): m_{4l}=123.5 GeV

Expected VBF-like signal (m_{4l}=120-130 GeV):

0.71±0.10 events, S/B: 5

VBF purity: 60%

VBF signal: 0.4 events

$S_{VBF}/(S_{ggF} + B)$: 1

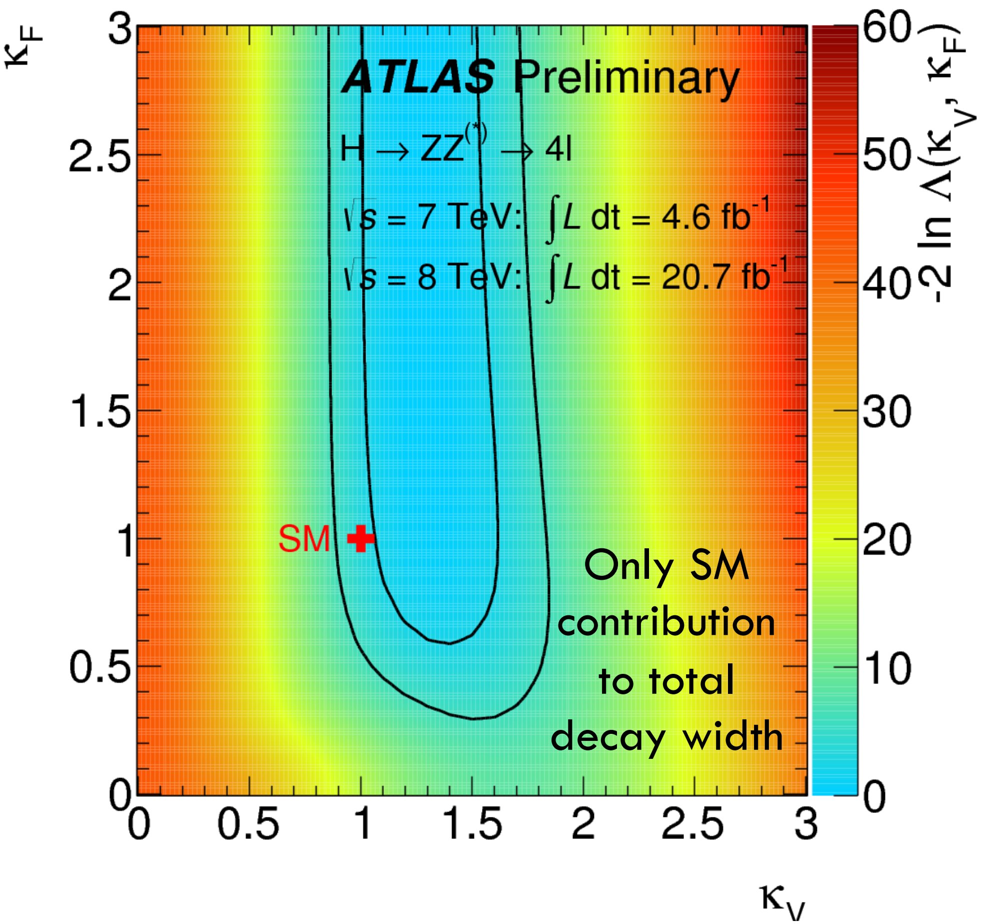
VBF candidates (m4l>160 GeV): 6

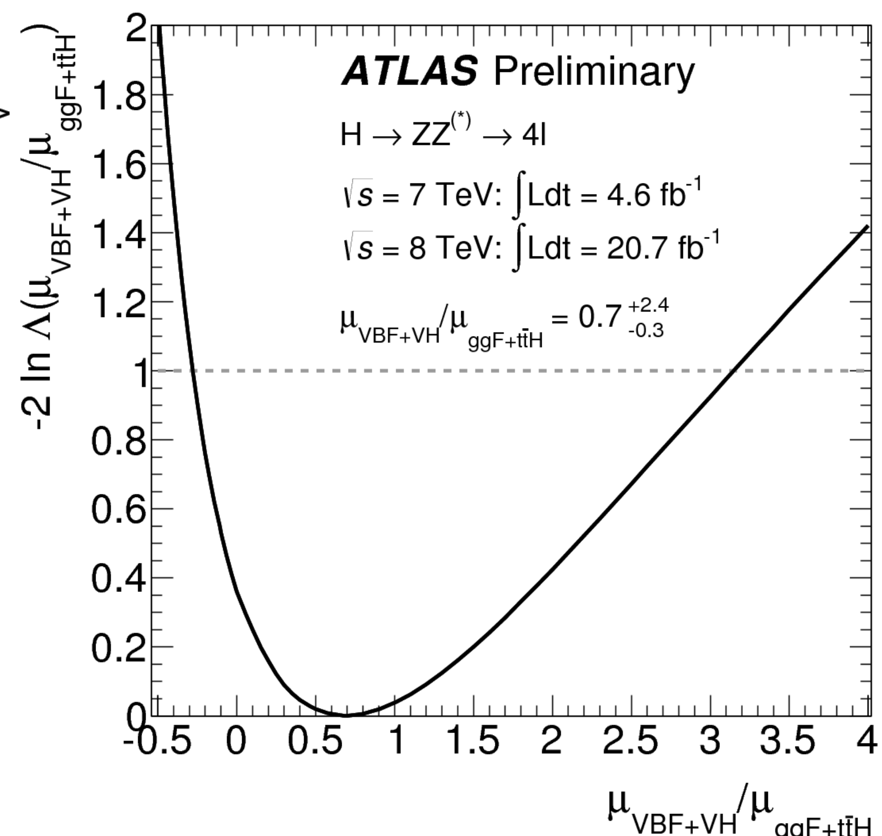
SM ZZ: 3.8±1.3 events

One observed VH candidate (m_{4l}=270.3 GeV)

Expected from SM ZZ production: 0.9±0.3 events

Fermion and Vector-Boson coupling strenghts





$\mu_{VBF+VH} / \mu_{ggF+ttH} = 0.7^{+2.4}_{-0.3}$

k_V and k_F are the ratios of the Higgs couplings to weak vector bosons and fermions to their respective SM expectations:

$$\kappa_V \equiv \kappa_Z = \kappa_W$$

$$\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

Details in A. Gabrielli's poster

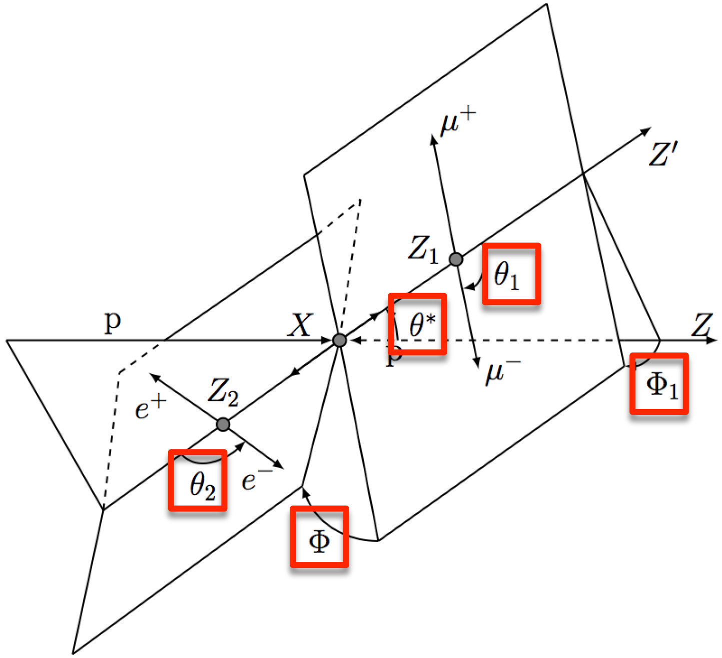
Details for the combination with other channels in M. Fanti's talk

Spin–Parity Analysis

- Using same event selection and background estimation as main analysis
- Restricted mass range: 115 GeV < m4l < 130 GeV (43 events observed)
- Different spin-parity states generated by LO JHU generator via ggF production: 0^+, 0^-, 1^+, 1^-, 2^+_m, 2^-
- Reweighted to match the POWHEG p_T spectrum (comparing 0+ samples)
- For 2^+_m state, qq production also simulated and gg/qq mixtures considered
- Two regions (improving sensitivity by ~5%)
  - high-S/B: (121-127) GeV
  - low-S/B: (115-121 U 127-130) GeV

Sensitive variables

- Intermediate boson masses: m_{12}, m_{34}
- production angles: Z_1 production angle θ^* and decay plane angle (Φ_1)
- Helicity angles: angle between the Z_1 and Z_2 decay planes (Φ) and decay angles of negative leptons (θ_1,θ_2)



Spin-Parity Discriminants

Several correlated observables to be combined: ***multivariate technique***

- ***J^P-MELA*** based on full theoretical calculation of the Matrix Element
  - Each event is assigned a probability that it comes from a particular spin-parity state: $p_{JP}(m_{4l}, m_{12}, m_{34}, \cos\theta^*, \Phi_1, \Phi, \cos\theta_1, \cos\theta_2)$
  - Corrected for detector acceptance, analysis selection, mispairing (4e, 4μ) using fully simulated signal MC
  - Discriminant: p0 /(p0 +p1)
- ***BDT*** trained for each spin-parity hypothesis pair using fully simulated signal MC
  - For 0^+-0^- discrimination, use 5 input variables only (θ^*, Φ_1 not included)
  - For all other hypothesis pairs, use full info of 7 variables

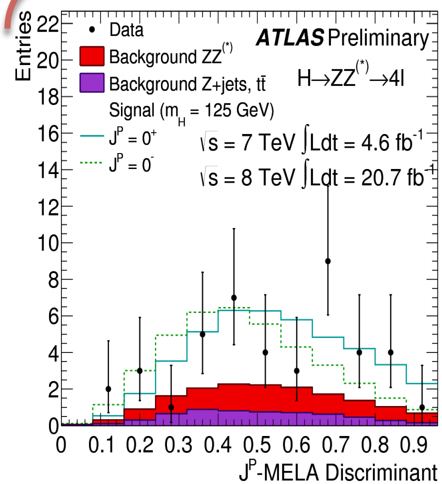
Systematic uncertainties

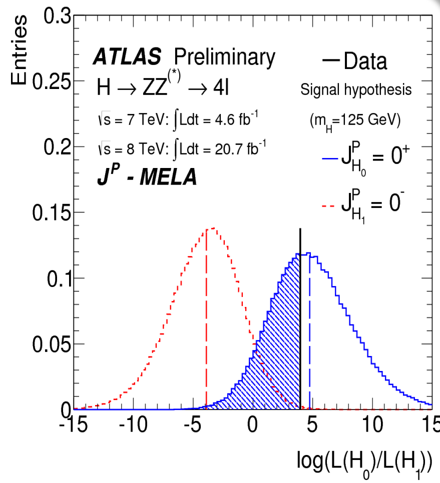
- ✓ Sources related to lepton identification, background estimation both on normalization and shape as in main analysis
- ✓ p_T-reweighting of JHU samples affecting high-S/B bin normalization by 1%
- ✓ 10% bin variation due to electron energy scale and resolution
- ✓ 10% bin migration for a possible variation of the assumed 125 GeV mass(negligible impact)

Future perspective in F. Cirotto's poster

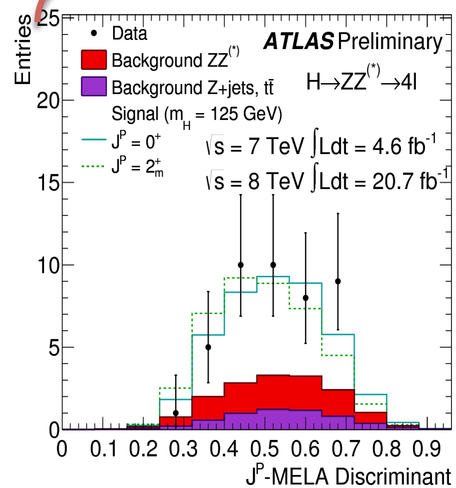
Spin–Parity Hypothesis testing

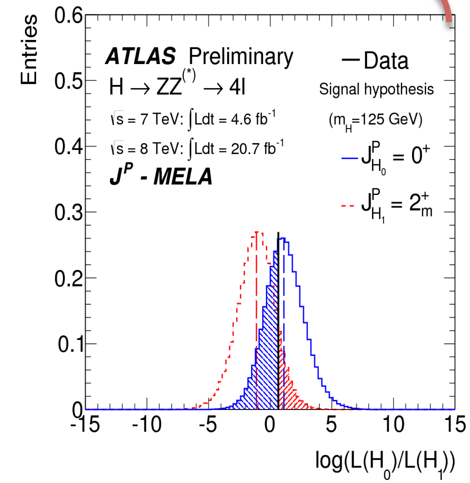
$0^+ - 0^-$





$0^+ - 2^+_m$





- Similar sensitivities of BDT and J^P-MELA
- Expected separation >2.5σ, except for 2^+_m (~1.5σ)
- **New boson compatible with SM 0^+ Higgs hypothesis when compared pair-wise with 0^-, 1^+, 1^-, 2^- for 2^+_m**

J^P	C.L.
0^-	99.6 %
1^+	99.4%
1^-	96.9%
2_m^+	81.8%
2^-	88.4%

Details in V. Ippolito's poster

Summary

- Updated results using the full 2011-2012 ATLAS dataset

- Inclusive analysis:
  - ✓ Single-channel discovery reached: **p_0 = 2.7 · 10-11 (6.6 σ) @ m_H=124.3 GeV**
  - ✓ Fitted mass: **124.3 $^{+0.6}_{-0.5}$ (stat) $^{+0.5}_{-0.3}$ (syst)**
  - ✓ Signal strength: **μ =1.7$^{+0.5}_{-0.4}$ @ m_H=124.3 GeV**

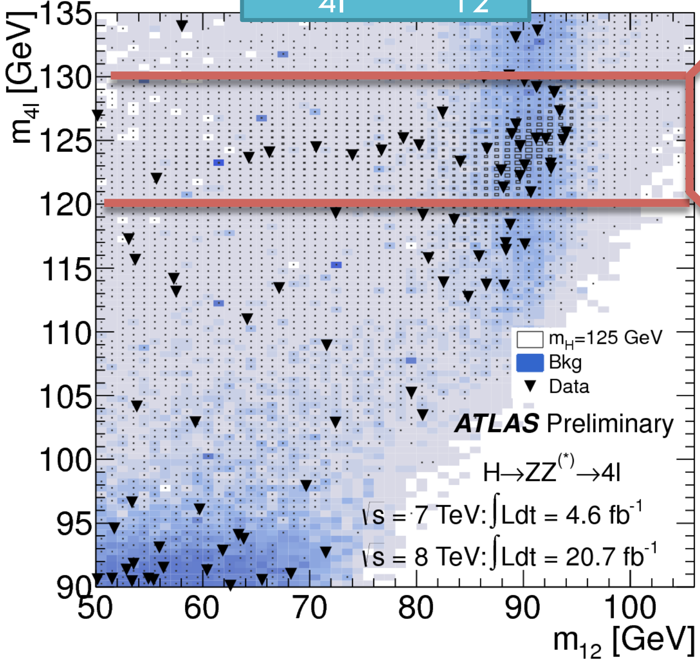
- H→4l candidate events sorted into ggF-, VBF-, VH-like categories for the first time:
  - ✓ VBF-like event with m_H=123.5 GeV observed, where 0.5 VBF signal events expected with S/B~1 (counting ggF signal production as background)
  - ✓ Coupling properties tested in simple benchmark models: $\lambda_{FV} = \kappa_F/\kappa_V$ > 0.3 @ 95% CL
  - ✓ Cross-section limits set on an additional resonance production for m_H>200 GeV via ggF or VBF+VH production processes

- BDT and J^P-MELA spin-parity analyses testing several spin-parity states: ggF only 0^+, 0^-, 1^+, 1^-, 2^- production and varying ggF/qq fraction for 2^+_m
  - ✓ New boson compatible with SM 0^+ Higgs hypothesis when compared pair-wise with 0^-, 1^+, 1^-, 2^+_m; comparison with 2^- inconclusive
  - ✓ 0^- and 1^+ hypotheses excluded at 97.8% CL or higher using CLs in favor of 0^+

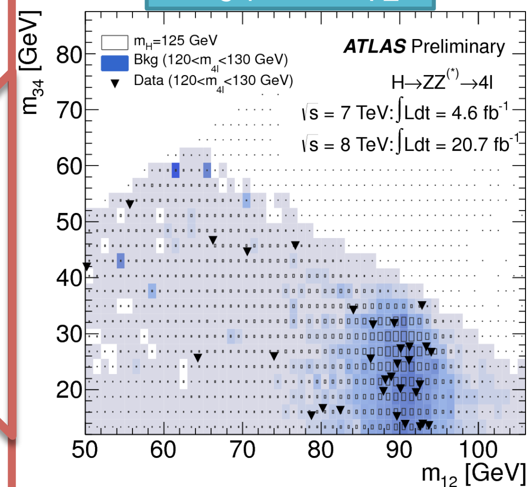
Backup

H→ZZ(*)→4l Inclusive Analysis: Selected events

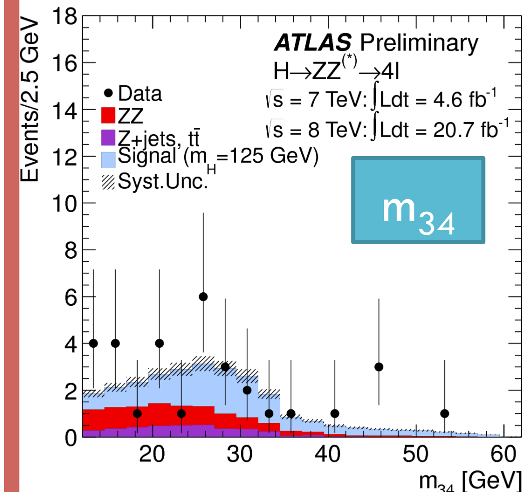
m_{4l} vs m_{12}



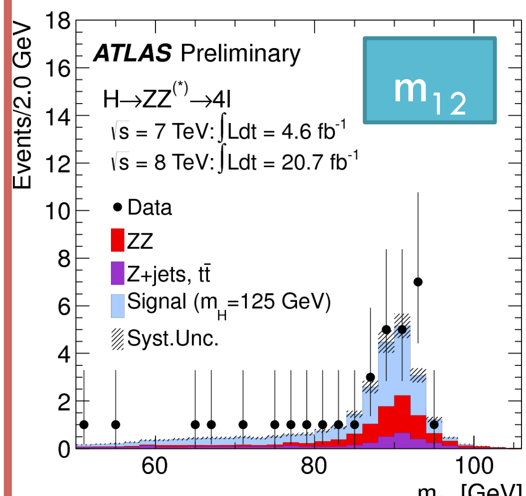
m_{34} vs m_{12}



m_{34}

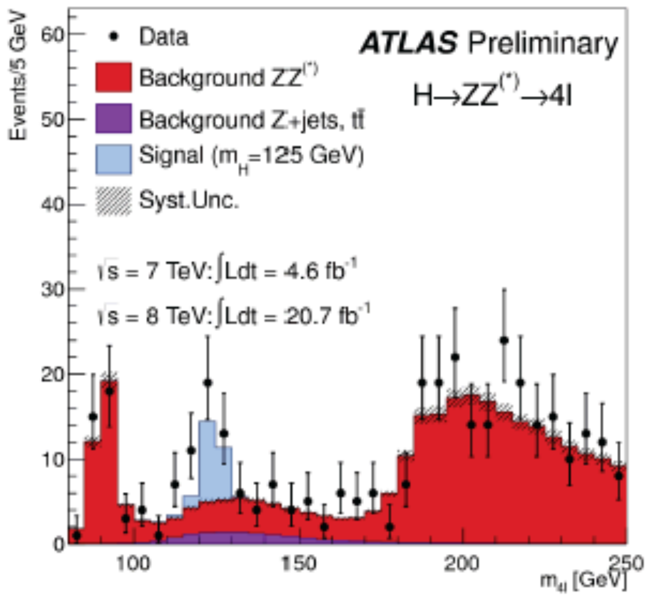


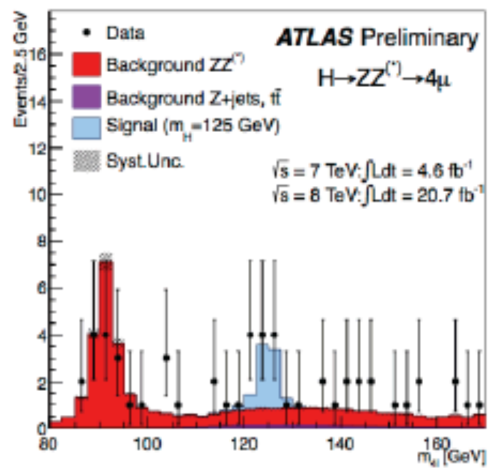
m_{12}

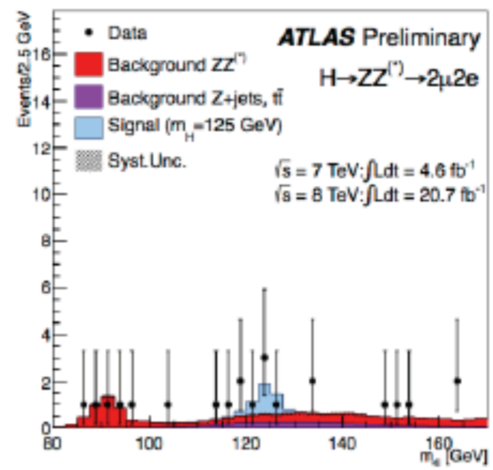


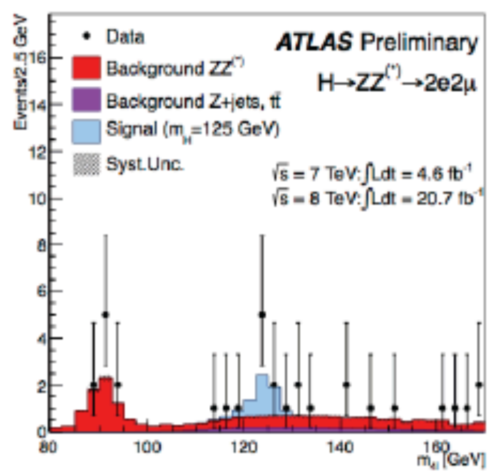
Selecting the mass range: $120 < m_{4l} < 130$ GeV

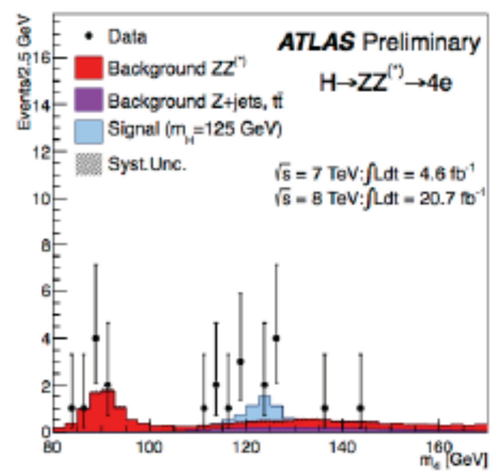
4-lepton invariant mass



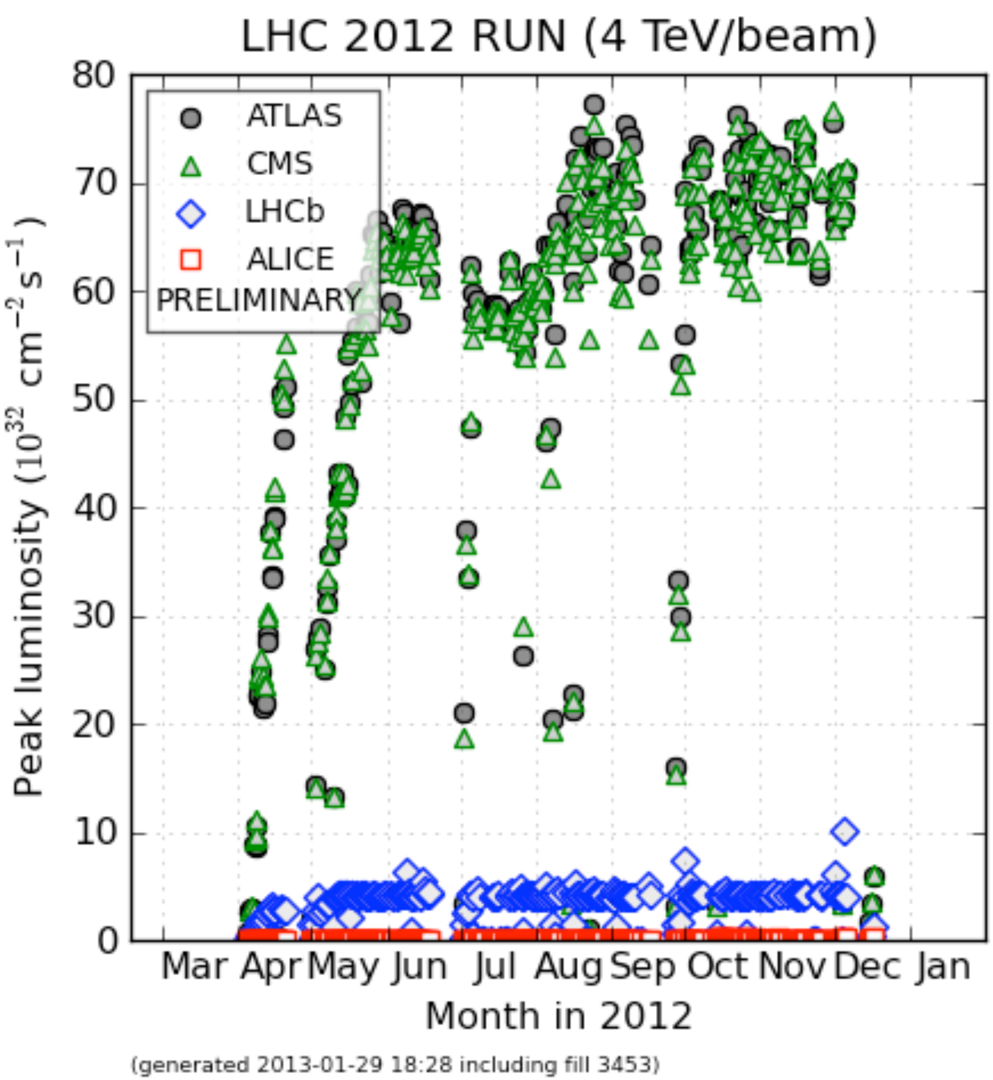








LHC Luminosity



Reducible Background estimate

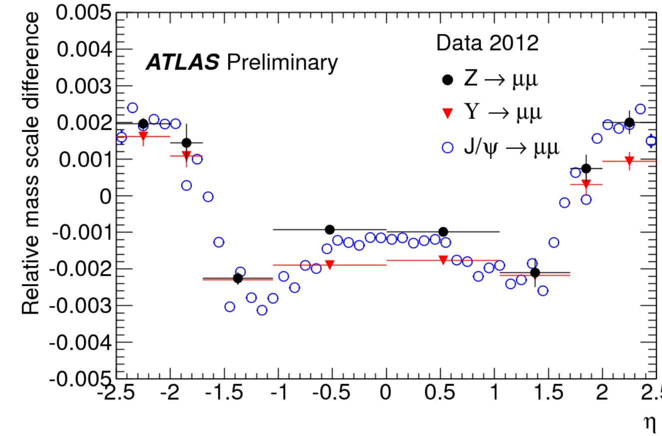
method	estimate at $\sqrt{s} = 8$ TeV	estimate at $\sqrt{s} = 7$ TeV
	4μ	4μ
m_{12} fit: $Z+$jets contribution	$2.4 \pm 0.5 \pm 0.6^{\dagger}$	$0.22 \pm 0.07 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.10 \pm 0.05 \pm 0.004$	-
	$2e2\mu$	$2e2\mu$
m_{12} fit: $Z+$jets contribution	$2.5 \pm 0.5 \pm 0.6^{\dagger}$	$0.19 \pm 0.06 \pm 0.02^{\dagger}$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02^{\dagger}$	$0.03 \pm 0.01 \pm 0.01^{\dagger}$
$t\bar{t}$ from $e\mu + \mu\mu$	$0.12 \pm 0.07 \pm 0.005$	-
	$2\mu 2e$	$2\mu 2e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$5.2 \pm 0.4 \pm 0.5^{\dagger}$	$1.8 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.9 \pm 0.4 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.3 \pm 0.6 \pm 0.5$	$2.8 \pm 0.4 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	4	0
	$4e$	$4e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed cuts	$3.2 \pm 0.5 \pm 0.4^{\dagger}$	$1.4 \pm 0.3 \pm 0.4$
$\ell\ell + e^{\pm}e^{\mp}$ inverted cuts	$3.6 \pm 0.6 \pm 0.6$	-
$3\ell + \ell$ (same-sign)	$4.2 \pm 0.5 \pm 0.5$	$2.5 \pm 0.3 \pm 0.5^{\dagger}$
sub-leading same sign full analysis events	3	2

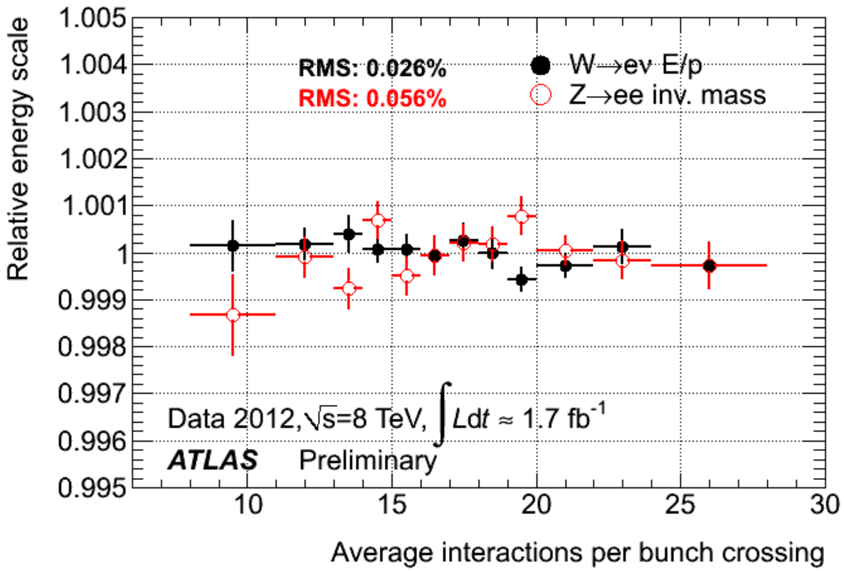
Approx. 80% of the irreducible background has m_{4l}<160 GeV

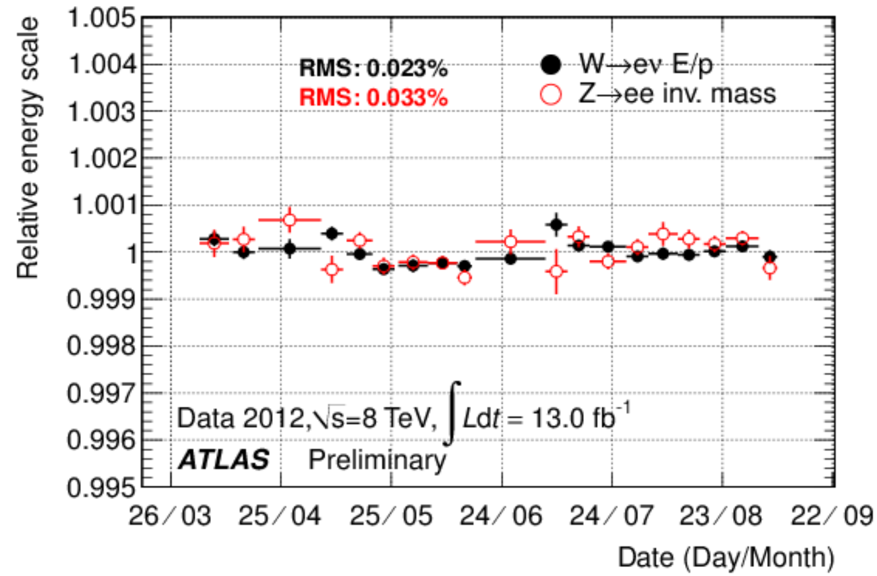
* m_{4l}<160 GeV

Mass Scale systematics

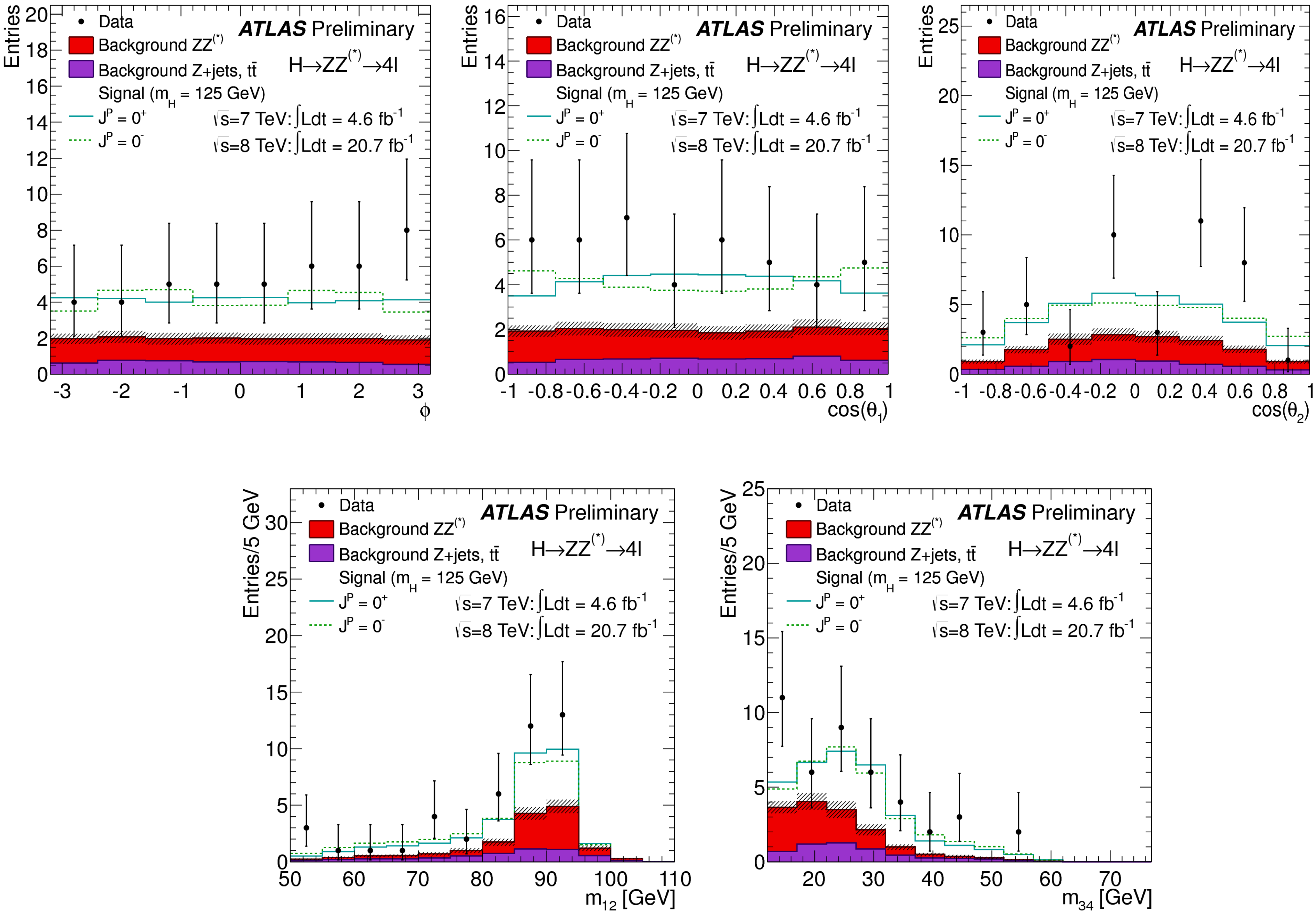
- Many sources of uncertainty studied
- Excellent stability over time, pileup conditions
- Compatible measurements using different objects (W, Z, Y,J/ψ)
- Good agreement with MC simulation eg. $(m-m_{PDG})/m_{PDG}$ reproduced to <0.2% for $Z\rightarrow\mu\mu$







Spin-Parity sensitive observables 0^+ VS 0^- Hypothesis Test



Event display of a 4e and a 4 μ candidates

m_{4l}=124.6 GeV

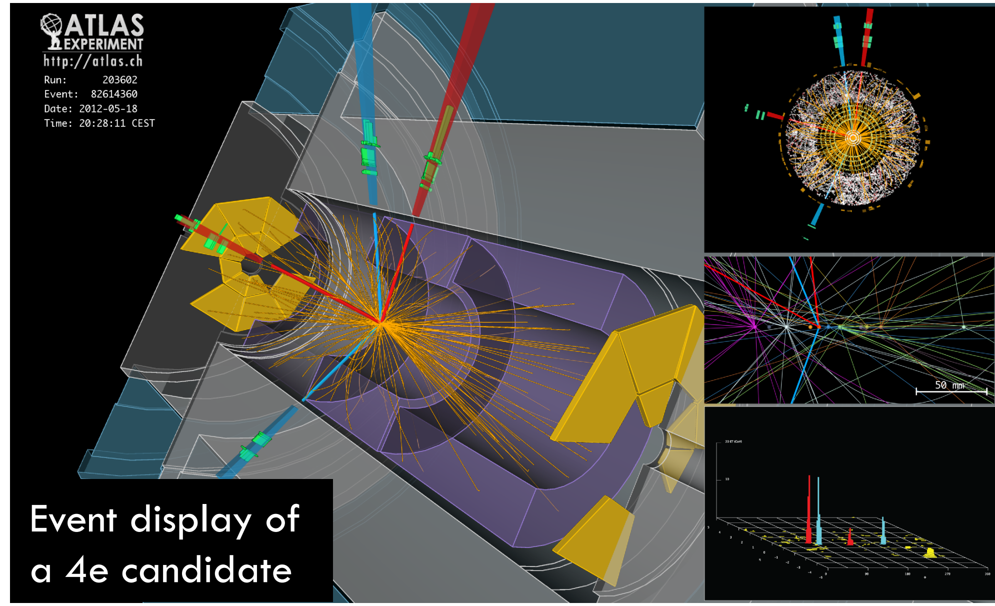
m_{12}= 70.6 GeV m_{34}= 44.7 GeV.

l1: pT,eta,phi=53.9 GeV,-0.40, 1.70.

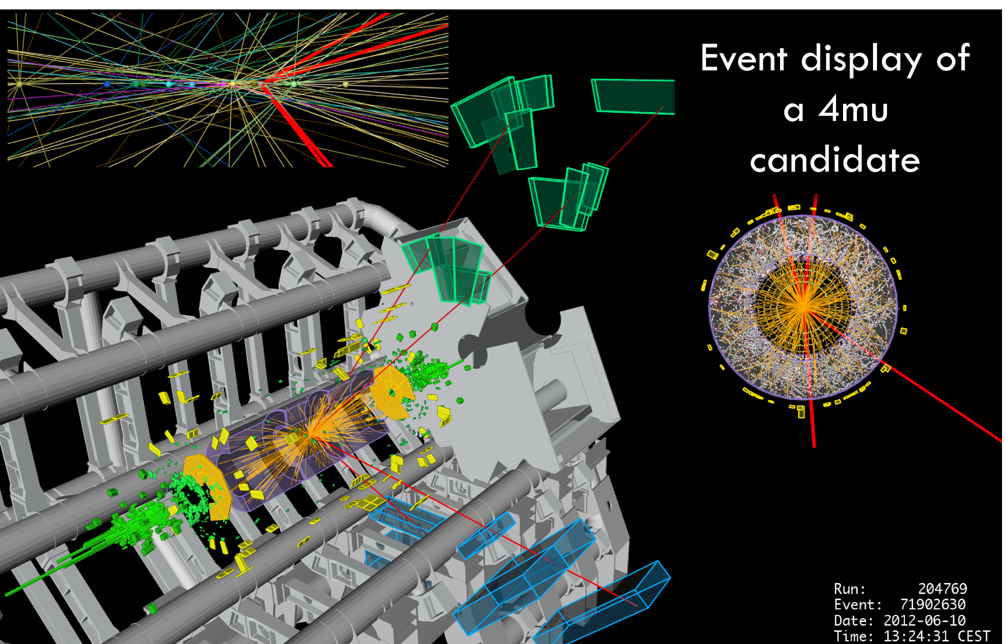
l2: pT,eta,phi=24.9 GeV,-0.33, -1.99.

l3: pT,eta,phi=61.9 GeV,-0.12, 1.45.

l4: pT,eta,phi=17.8 GeV,-0.52, 2.84.



Event display of a 4e candidate



Event display of a 4mu candidate

m_{4l}=127.4 GeV.

m_{12}=86.6 GeV m_{34}=31.6 GeV.

l1: pT,eta,phi=47.6 GeV,0.80, -1.66.

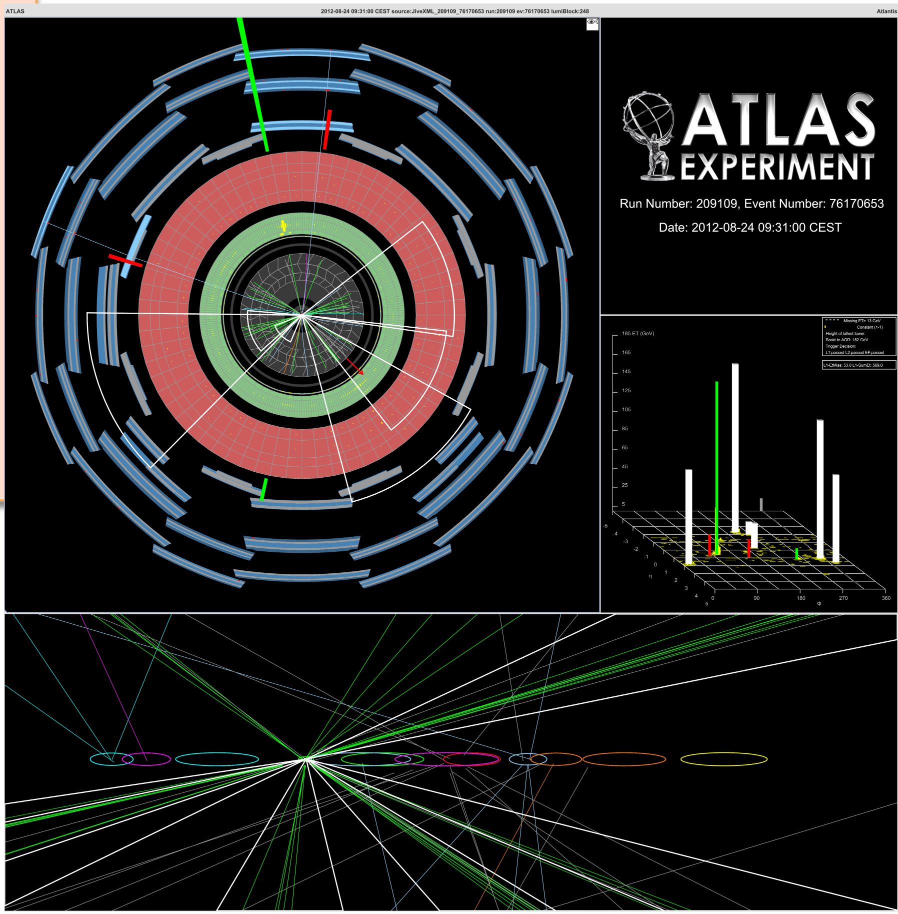
l2: pT,eta,phi=36.2 GeV,1.30, 1.33.

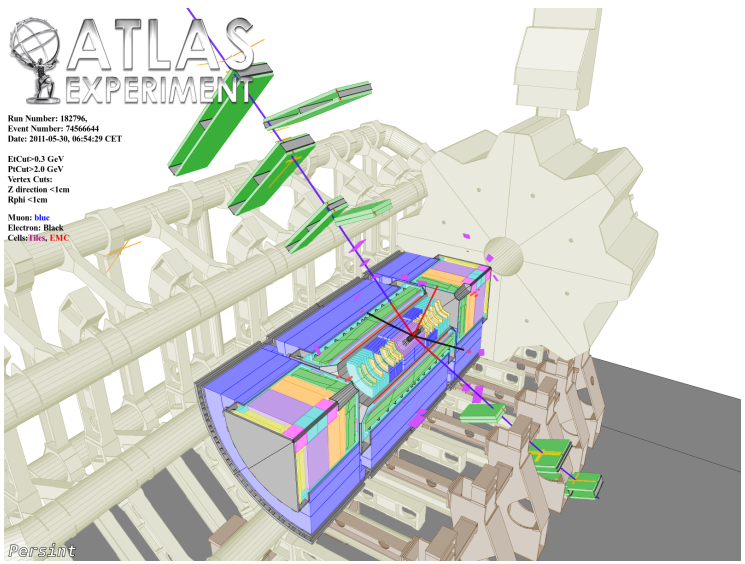
l3: pT,eta,phi=26.4 GeV,0.47, -2.52.

l4: pT,eta,phi=7.2 GeV,1.85, 1.65.

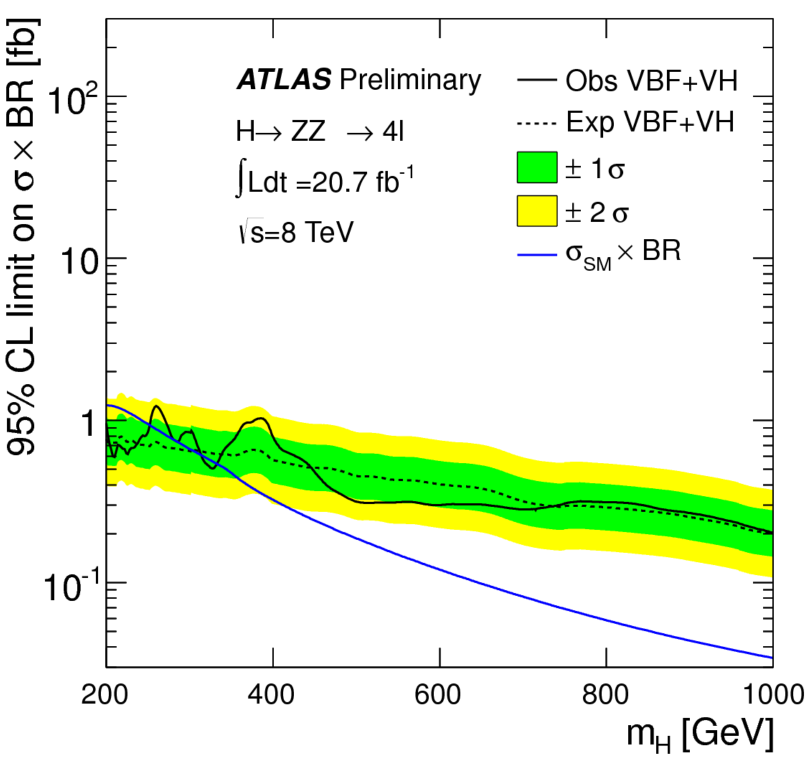
Event display of a 2e2mu VBF candidate

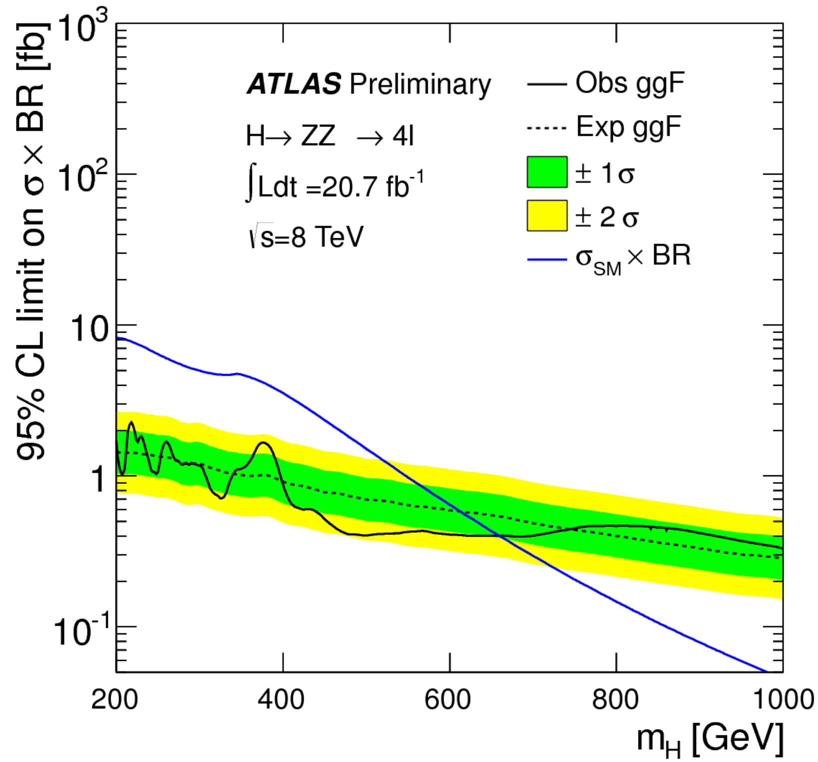
m4l=123.5 GeV. m12=94.0 GeV, m34=26.7 GeV.
e1: pT,eta,phi=181.0 GeV,0.59, 1.78.
e2: pT,eta,phi=11.5 GeV,1.21, -1.79.
mu3: pT,eta,phi=22.0 GeV,0.79, 1.44.
mu4: pT,eta,phi=18.9 GeV,0.98, 2.84.
pT4ell=200.9 GeV. ETmiss=40.6 GeV, VBF
jet1: pT,eta,phi=140 GeV, -2.20, -2.75 VBF
jet2: pT,eta,phi=109 GeV, 1.19, -0.91
jet3: pT,eta,phi=76 GeV, 1.90, 0.26,
jet4: pT,eta,phi=66 GeV, 1.67, -0.51.





Search for an additional high mass SM-like Higgs resonance





High-mass signal assumed to have SM-like width
(estimated using the Complex-Pole-Scheme)